Recent Progress on Calibration

BNL LBNE mtg S.White 5/7/10

* "LBNE energy calibration using a 100 MeV electron accelerator"-SNW& Vitaly Yakimenko http://arxiv.org/abs/1004.3068
* "Free p0 s for LBNE calibration" SNW lbne note

Accelerator Beam

* understanding EM response of LBNE over wide energy range critical for most analyses
* Super K made good use of a 5-16 MeV medical accelerator -**Mitsubishi ML-15MIII**
* They used a conventional secondary beam (requires long beamline)
* we proposed a new principle based on large angle Rutherford scattering

Wide angle electron scattering

Approximations to Hofstadter's form:

$$\text{Rutherford}[\theta\_,\ Z\_,\ \text{EeMeV}\_] := 1/4\,(Z * \alpha_{EM})^2\ \frac{\hbar c1^2}{\text{EeMeV}^2}\ \text{Csc}[\theta/2]^4$$

$$\text{Mott}[\theta\_,\ Z\_,\ \text{EeMeV}\_] := \text{Rutherford}[\theta,\ Z,\ \text{EeMeV}] * \text{Cos}[\theta/2]^2 \left(1 + \frac{\pi * Z * \alpha_{EM} * \text{Sin}[\theta/2] * (1 - \text{Sin}[\theta/2])}{\text{Cos}[\theta/2]^2}\right)$$

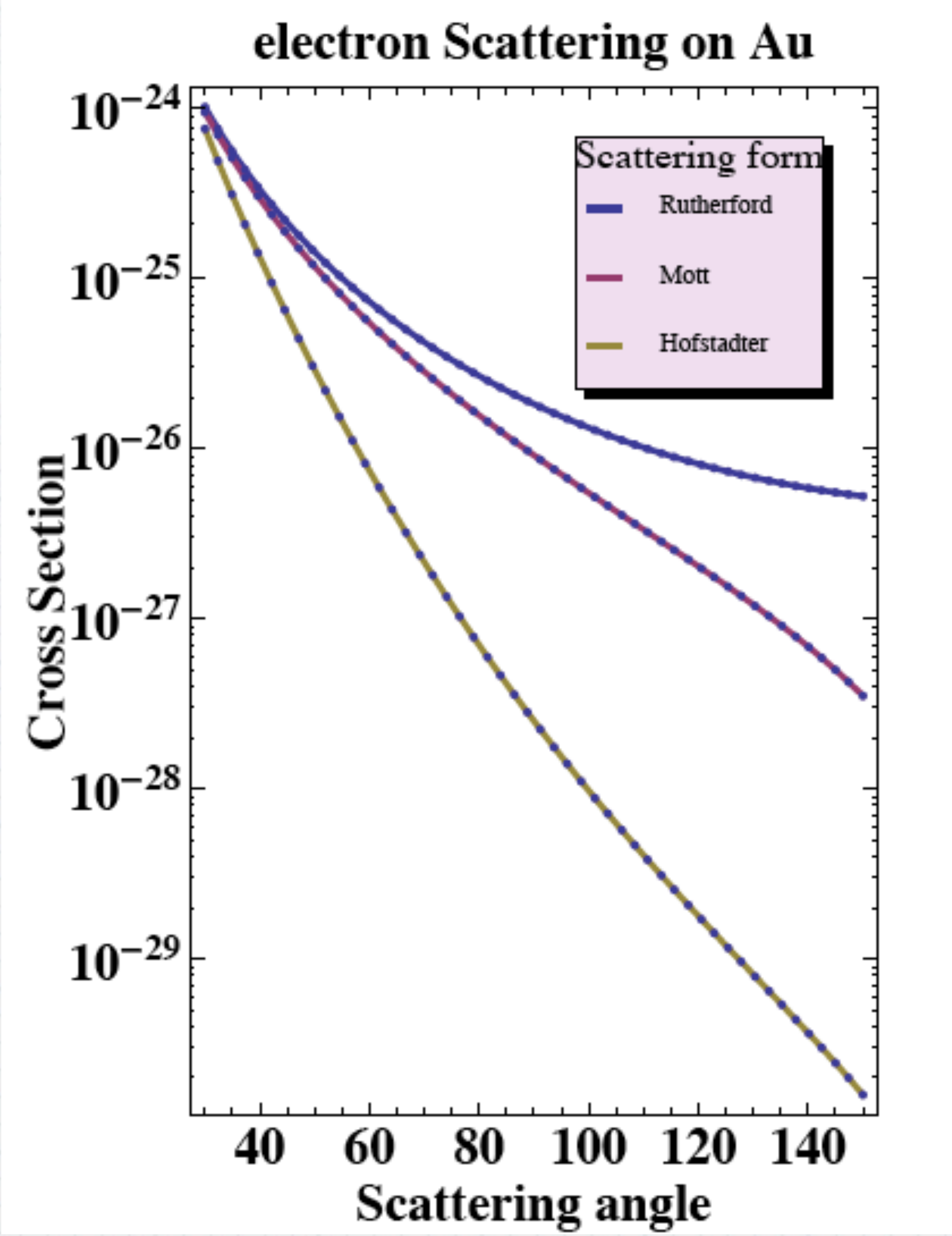
$$Q[\theta\_,\ \text{EeMeV}\_] := \frac{2 * \text{EeMeV}}{\hbar c}\ \text{Sin}[\theta/2]$$

$$\rho[r\_,\ a\_] := \frac{1}{8\,\pi\,(a)^3}\ \text{Exp}[-r/a]$$

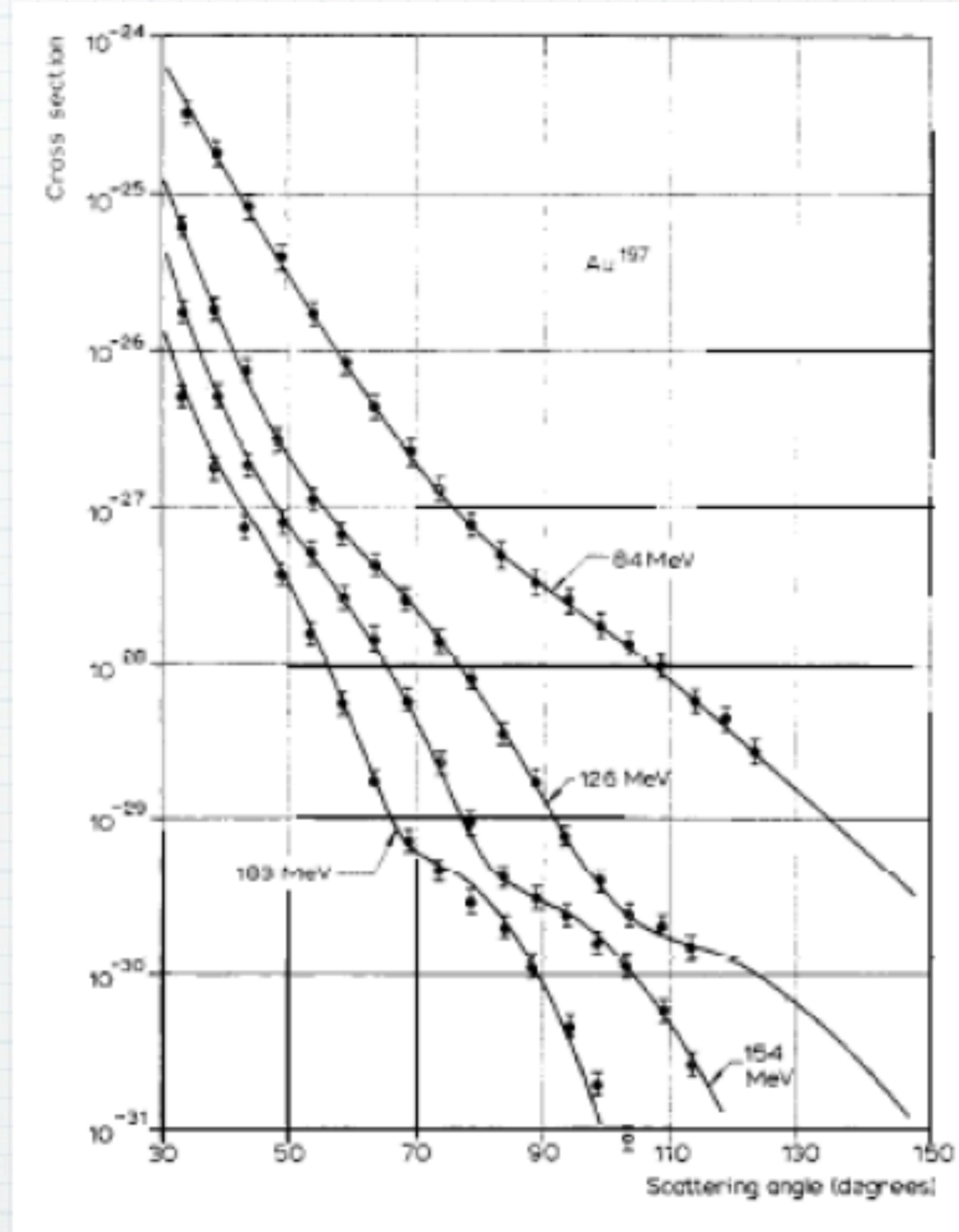
$$\text{FormFactor}(\theta\_,\ a\_,\ \text{EeMeV}\_) := \frac{4\,\pi \int_0^{\infty} r\,\rho(r,a)\sin(r\,Q(\theta,\text{EeMeV}))\,dr}{Q(\theta,\ \text{EeMeV})}$$

$$\text{Hofstadter}[\theta\_,\ Z\_,\ \text{EeMeV}\_,\ a\_] := \text{Mott}[\theta,\ Z,\ \text{EeMeV}] * \text{FormFactor}[\theta,\ a,\ \text{EeMeV}]^2$$

this calculation

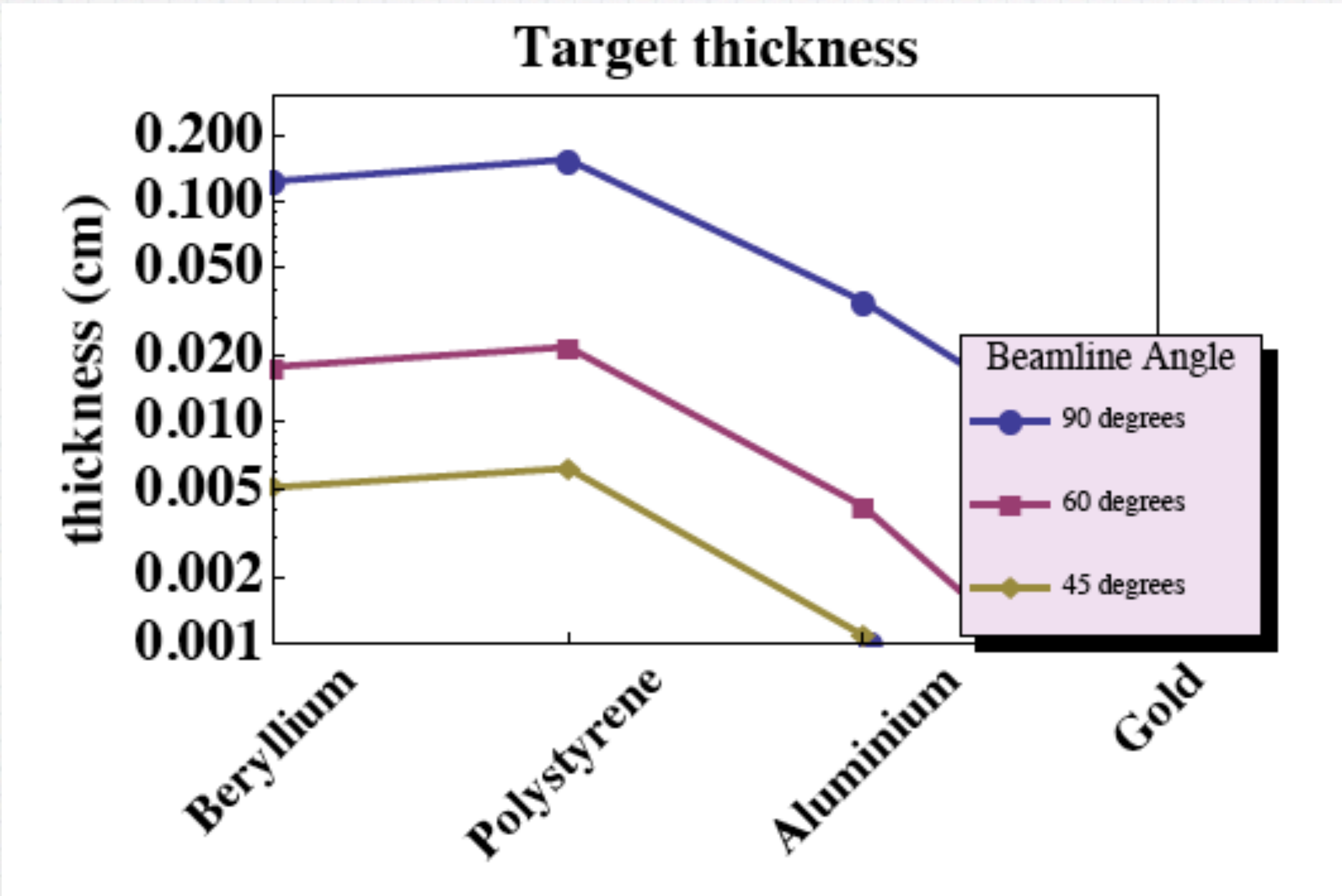


Hofstadter

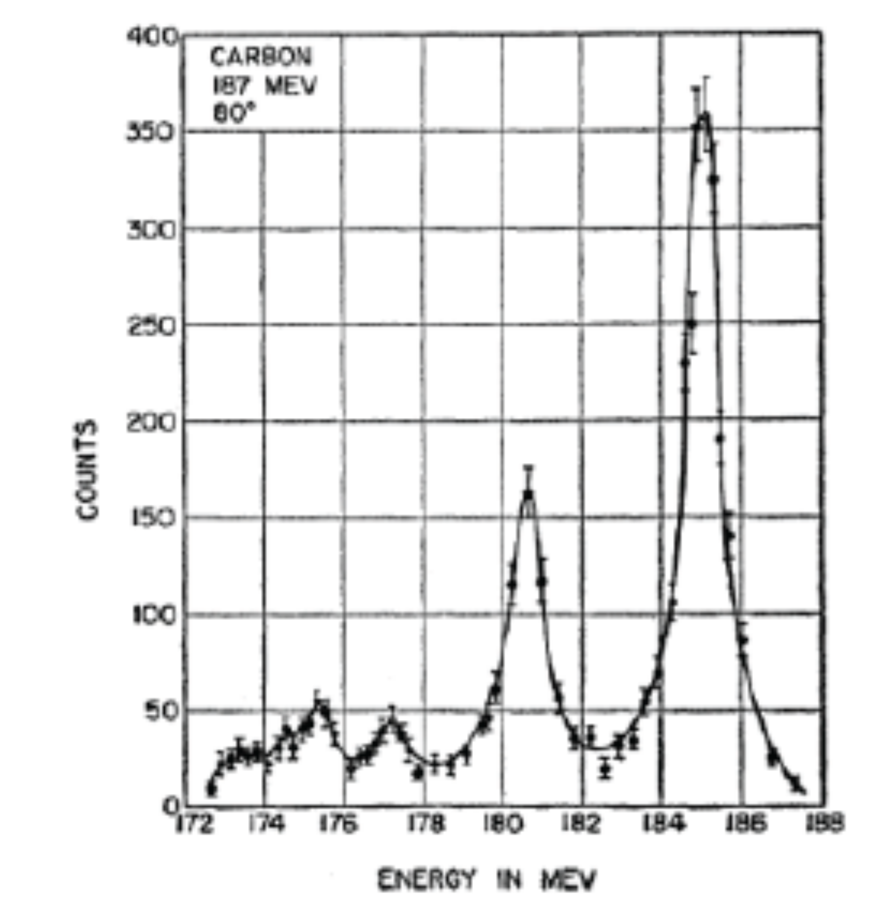


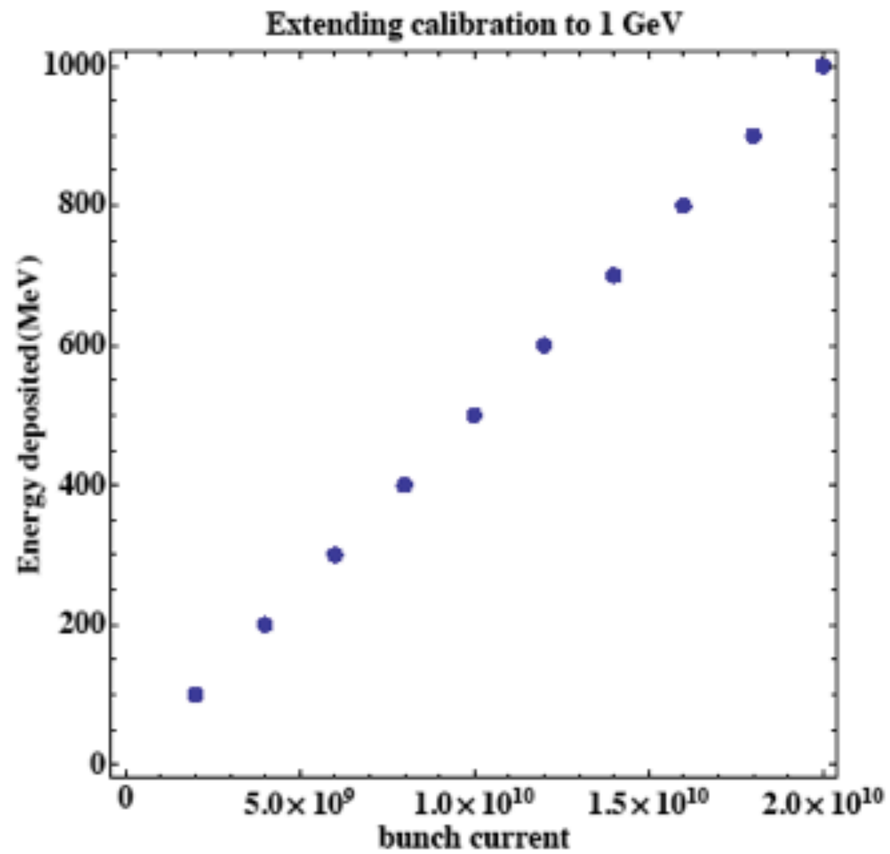
$$t90 = \text{Table}\left[.5 * \left(\frac{\text{Foils[[i, 3]]}}{M_p * \text{Foils[[i, 2]]}} * \text{Correction[[i]]} * \text{Flux} * d\Omega * \text{Hofstadter[90 * Degree, Foils[[i, 1]], 62, Foils[[i, 6]]]}\right)^{-1}, \{i, 4\}\right];$$

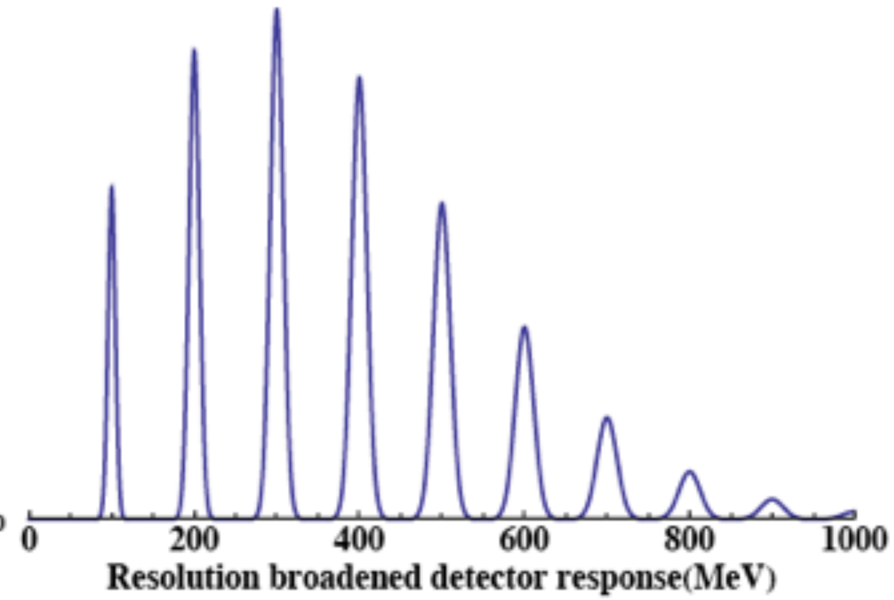
	Beryllium	Polystyrene	Aluminum	Gold
45^0	0.00507424	0.00619767	0.00108573	0.0000493743
60^0	0.0178675	0.0219929	0.00417395	0.000283
90^0	0.123976	0.15564	0.0354221	0.0050626



Interesting features for calibration







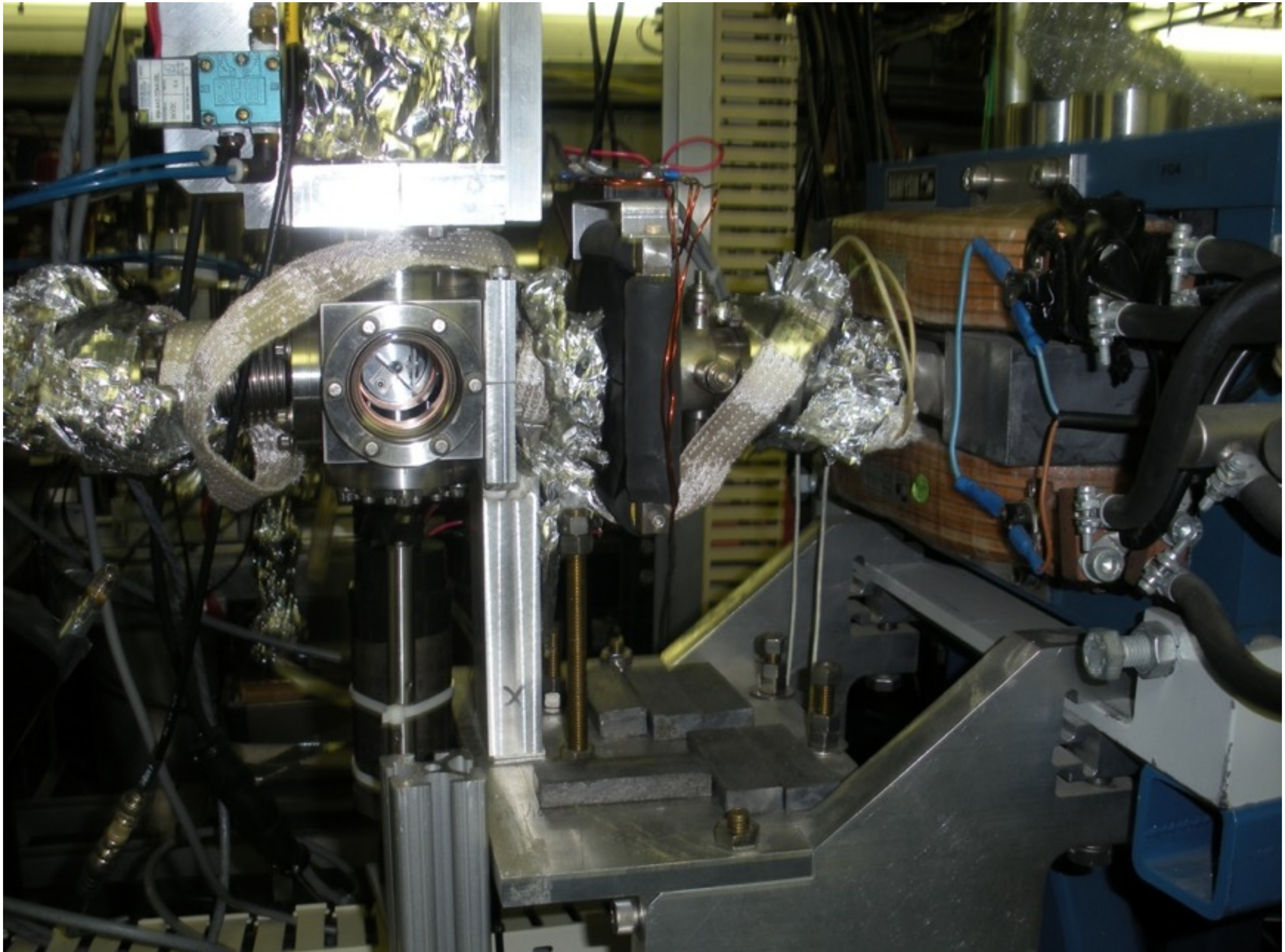
Custom made turn-key accelerator

Item	Value
RF operating frequency	2856 MHz
RF pulse flat-top duration	3 μs
Max. RF input power	10 MW
Max. accelerating gradient	100 MV/m
Max. beam energy at gun output	4.5 MeV
Bunch charge	0.1-1 nC
Repetition rate	10 Hz
RF operating frequency	2856 MHz
RF pulse flat-top duration	3 μs
Max. RF input power	15 MW
Max. accelerating gradient	20 MV/m
Max. energy gain per section	60 MeV
Repetition rate	10 Hz

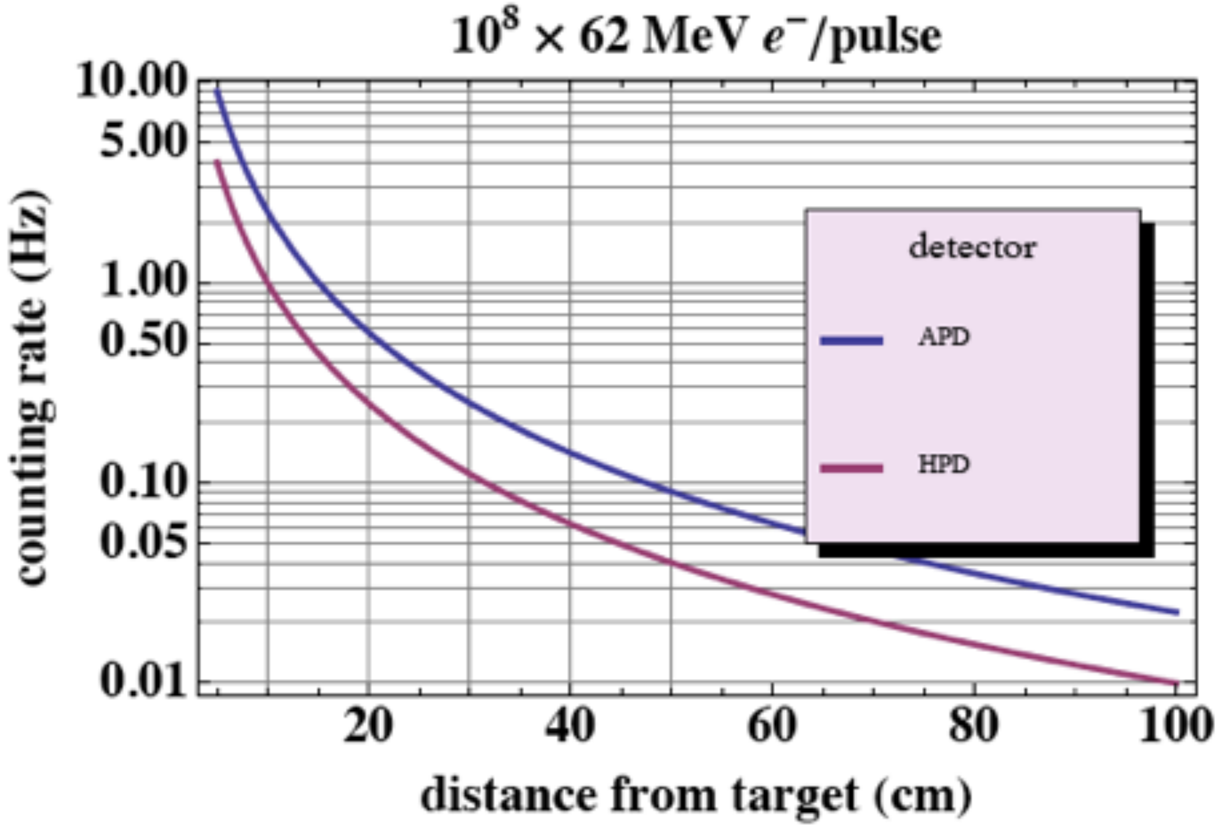
The approximate breakdown of the total cost is as follows:

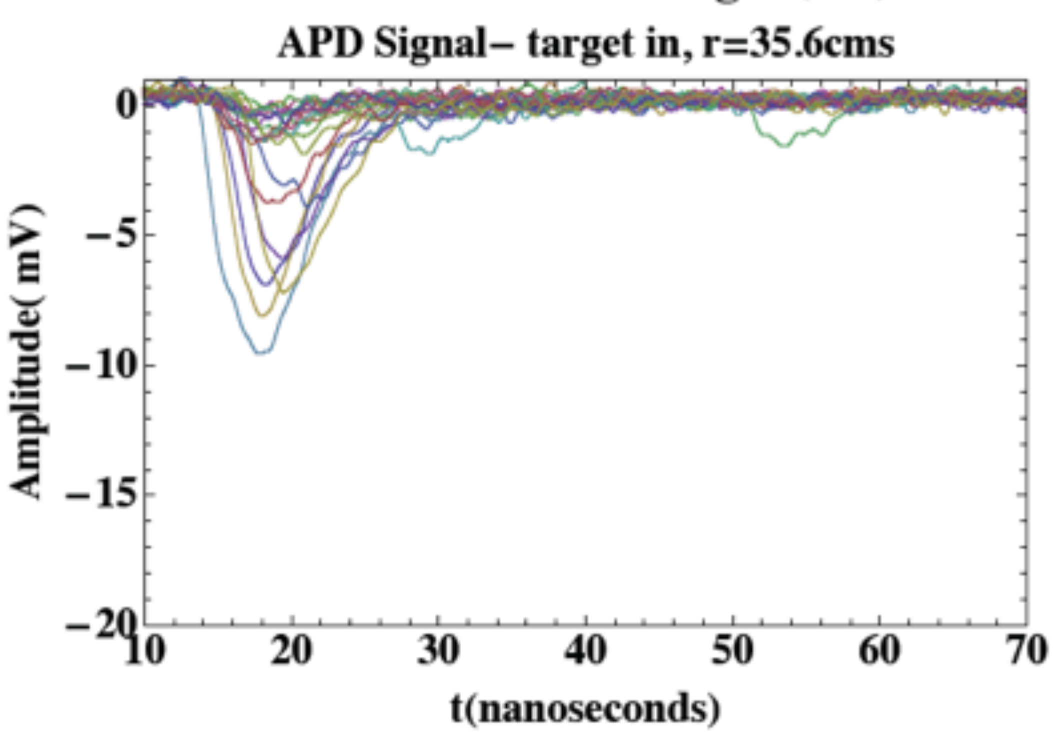
- Photoinjector gun system: $440,000
- Photocathode drive laser system: $481,000
- 100 MeV linear accelerator system: $628,000
- RF power system: $1,244,000
- Installation and commissioning support: $129,000

the beamline

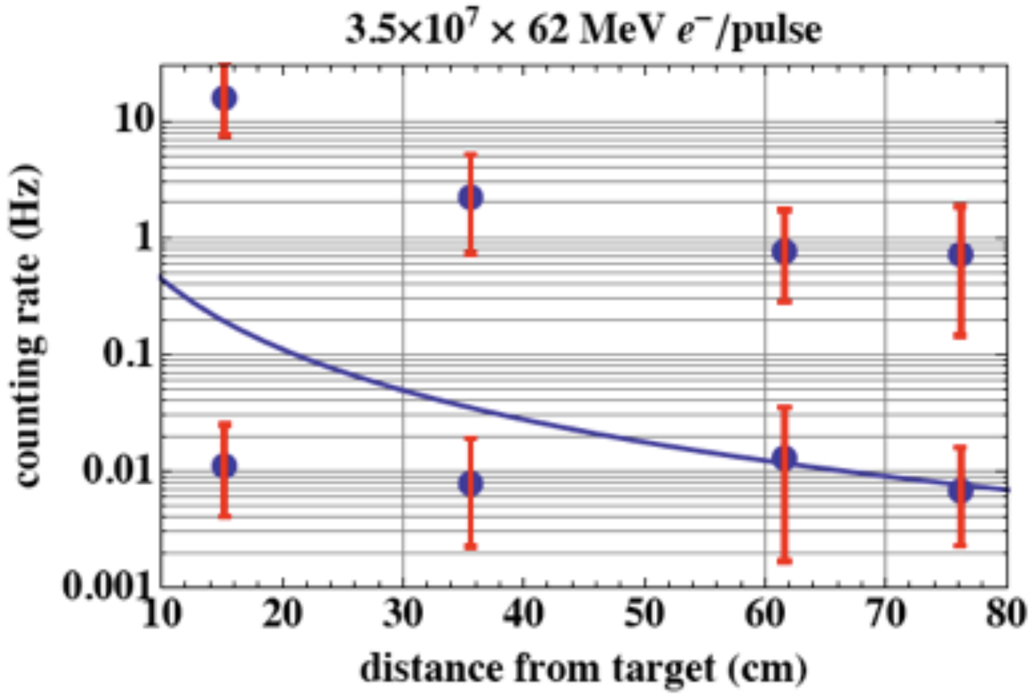


Initial tests (Al)





- "target out" background well below scattered rate
- "target in" rate ~10* calculation
- signal has v=c
- 1 X0 not effective
- concluded few MeV gamma



Al is very messy!

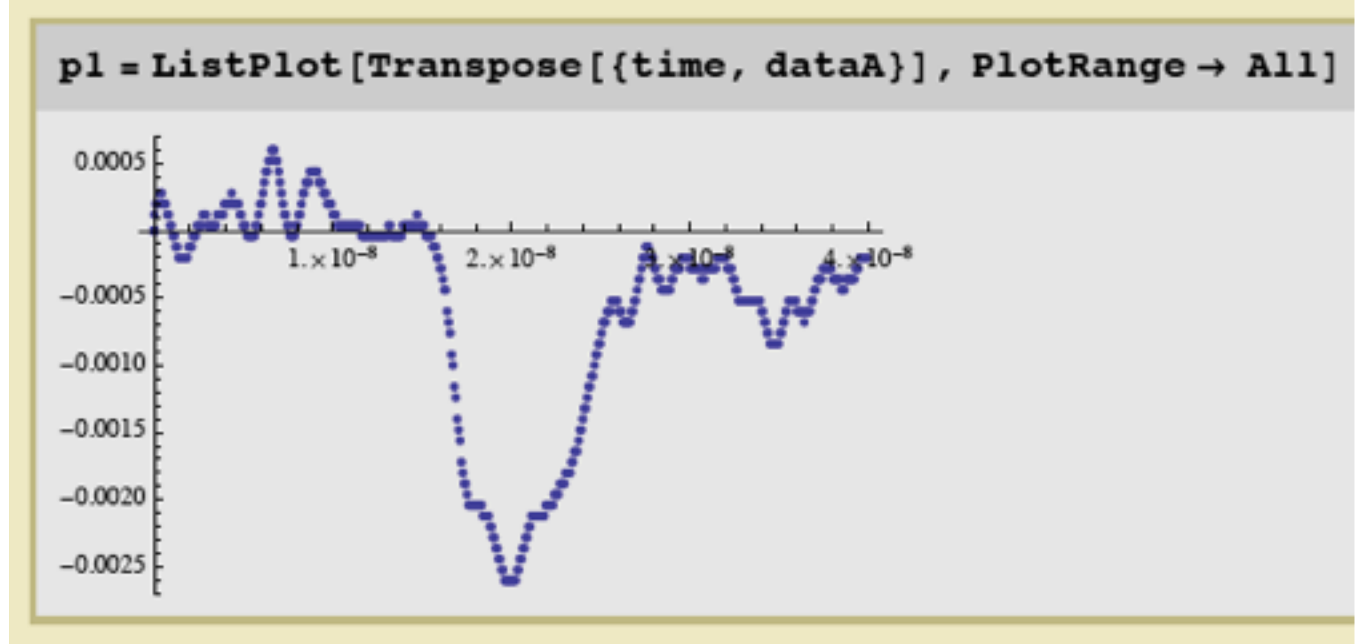


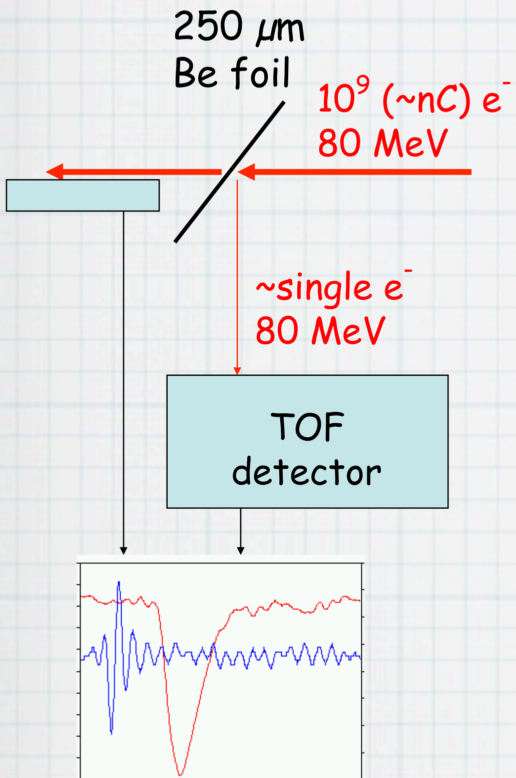
TABLE 27.4
Energy levels of ^{27}Al

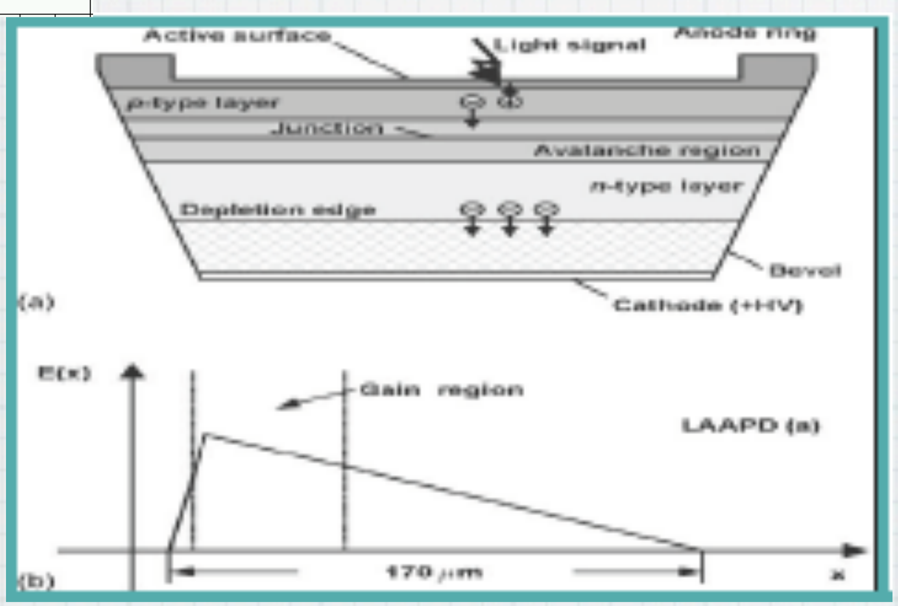
E_x [keV]	$2J^\pi;2T$	τ_m	E_x [keV]	$2J^\pi;2T$	τ_m or Γ	E_x [keV]	$2J^\pi;2T$	τ_m or Γ
0	5^+	stable	7997 *1*	9		9600.7 9	3	12 *2* eV
843.76 *3*	1^+	50 *2* ps	8037 *1*	7	0.62 5 fs	9599.2 *14*	3^-	2.5 *2* keV
1014.45 *3*	3^+	2.15 *10* ps	8043 *2*	$(5^+–9^+)$		9628.5 9	1^-	2.76 *14* keV
2211.1 *6*	7^+	38.4 *9* fs	8065 *2*	$(3, 5)^+$	$J \times 29$ *8* as	9634.5 9	5^+	18 *5* eV
2734.9 *7*	5^+	12.9 *18* fs	8097 *1*	5		9658 *2*		
2982.00 *5*	3^+	5.7 *3* fs	8130 *3*	1^+		9664.7 *8*	5^+	24 *8* eV
3004.2 *8*	9^+	85 *5* fs	8136 *1*	5		9664.8 *20*	1^-	5.82 *10* keV
3680.4 9	1^+	7.8 *17* fs	8182.1 *13*	3^-		9692 *3*		
3956.8 *4*	3^+	3.6 *3* fs	8287 *1*	9^-		9715.9 *8*	3^+	
4054.6 *5*	1^-	10.6 *18* fs	8324 *1*	5^+		9742 *3*		
4410.2 *4*	5^+	1.7 *2* fs	8361 *3*			9762.8 *8*	5^+	18 eV
4510.3 *5*	11^+	320 *20* fs	8376 *1*	$(3, 5)^+$		9796.3 9	7^+	4 *3* eV
4580.0 *8*	7^+	7.7 *8* fs	8396 *1*	11		9821.6 9	3^+	18 eV
4811.6 *5*	5^+	2.2 *3* fs	8408 *3*			9834.4 *10*	1^-	3.0 keV
5155.6 *8*	3^-	3.3 *4* fs	8420.7 *10*	$(3, 5)^+$		9839.7 *10*	5	1.0 *2* eV
5248.0 *6*	5^+	< 6 fs	8442 *1*	7	0.72 *14* fs	9846.6 *10*	1^+	210 eV
5419.9 *9*	9^+	< 20 fs	8490.3 *12*	5^+		9867 *3*		
5432.8 *10*	7	10 *3* fs	8521 *2*	$(1–7^+)$		9883 *3*		
5438.4 *8*	5^-	8 *6* fs	8537 *1*	5		9893 *2*		
5499.8 *8*	11^+	< 10 fs	8553.0 *3*	3		9921.9 9	3^-	1.8 keV
5550.9 *5*	5	3.8 *7* fs	8586 *1*	7		9930.4 9	1^-	1.35 keV
5667.3 *12*	9^+	16 *4* fs	8597.6 *3*	3^-	0.56 *4* eV	9941.3 *9*	7	
5751.6 *10*	1^+	< 15 fs	8675 *1*	$(7, 9^+)$	$J \times 18$ *5* as	9953.0 *16*		
5827.0 *8*	3^-	< 30 fs	8693 *2*	(9–13)		9955.5 *10*	3	
5960.3 *7*	7	2.4 *17* fs	8708.7 *3*	1^+	7.6 *6* eV	9960.3 *9*	5^-	8 eV
6080.8 *9*	3	4.8 *11* fs	8716.6 6			9962.8 *9*	5^+	12 eV
6115.8 *6*	5		8732.2 *5*	7^-	0.19 *3* eV	9976.8 *9*	$(5, 7)^+$	11 *2* J^{-1} eV
6158.4 *7*	3^-	< 20 fs	8753.6 6	5	1.05 *13* eV	9990.8 *9*	7^-	10 eV
6284.7 *15*	7^+	7 *3* fs	8774.2 6	5^+	3.7 *3* eV	9999.9 *10*	5	
6462.8 *13*	5	1.12 *12* fs	8804 *1*			10008 *3*		
6477.3 *9*	7^-	2.6 *4* fs	8825 *3*			10024.3 *9*	5^+	35 eV
6512.2 *11*	9	14 *3* fs	8861 *3*			10075 *3*		

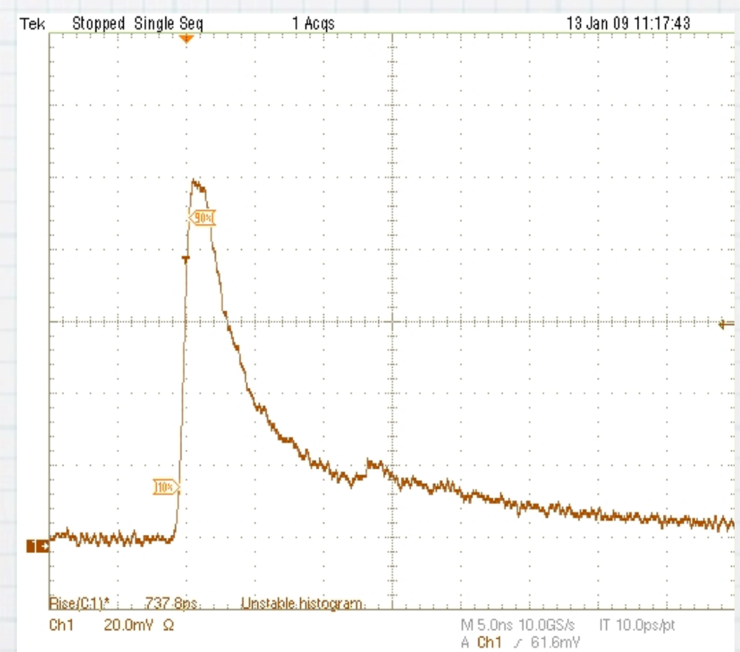
Beryllium is excellent!

last week had 2nd Beryllium run with more controlled
ATF conditions. Just starting analysis today. It looks very good.

Why is a 100 MeV, single electron, 3 picosecond beam interesting?







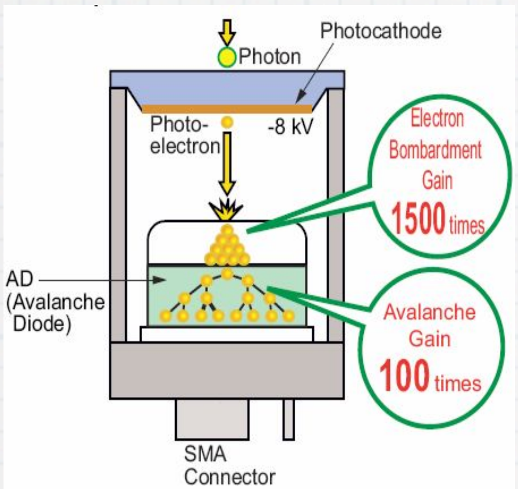
Deep diffused avalanche photodiode

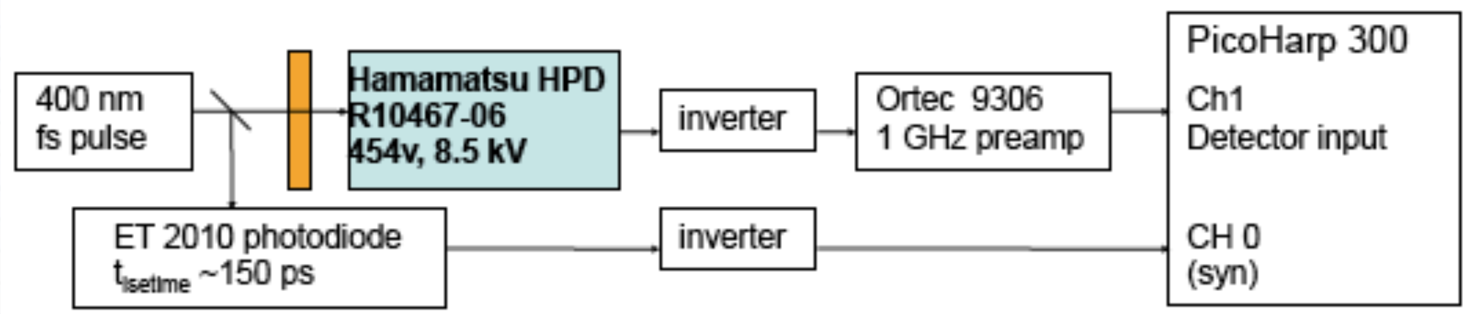
650 picosecond risetime (β's)

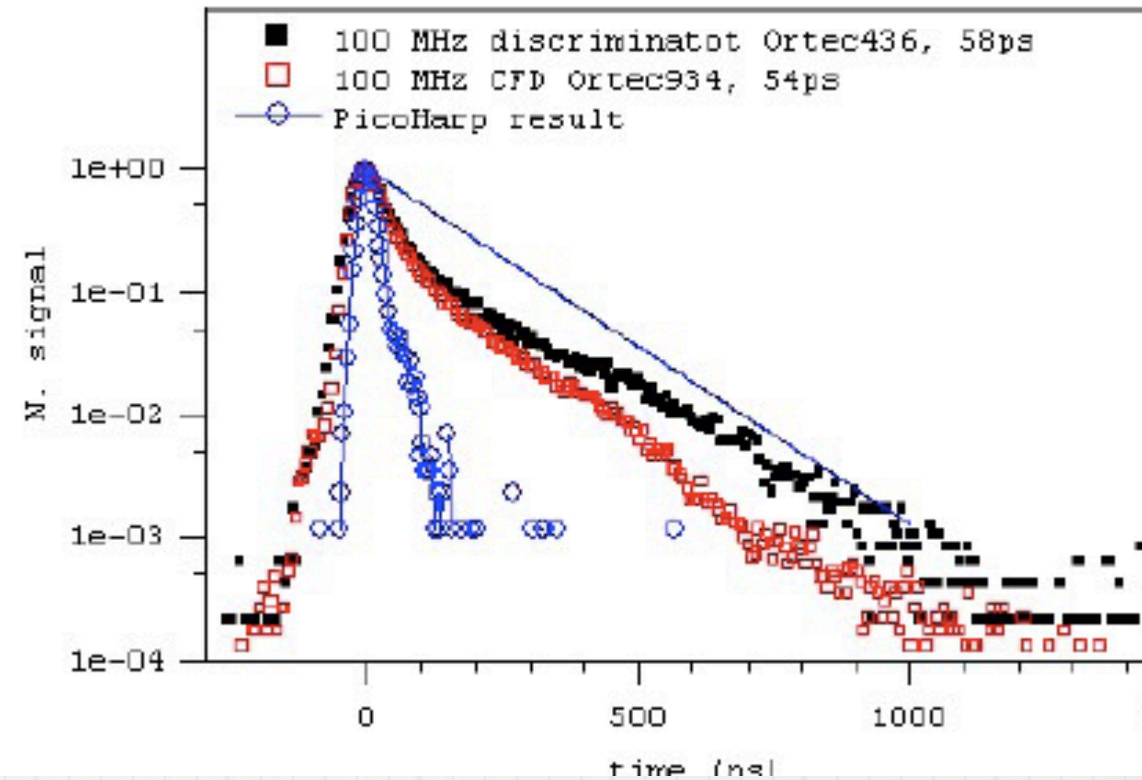
"A 10 picosecond time of flight detector using APD's", SNW et al.

High-speed Hybrid Photodetector in Single-photon Counting

Thomas Tsang, Instrumentation Division
Sebastian White, Physics Department

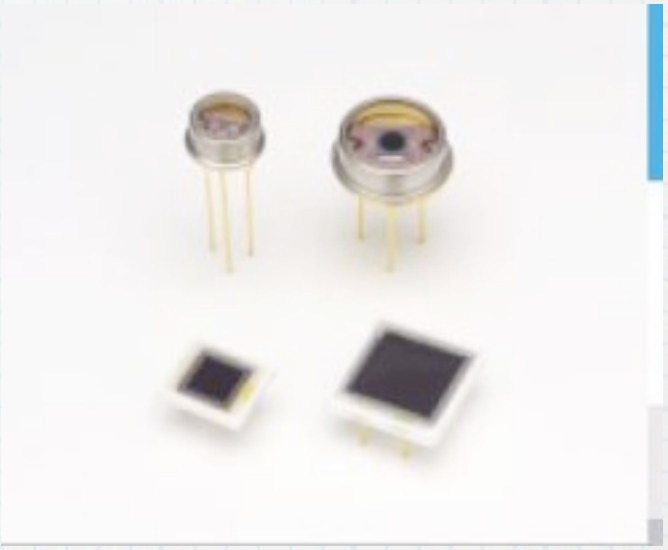






- we measured 11 psec single photon jitter
- lifetime>250*MCP
- rates to 100 Mhz
- will test at ATF w. C-radiator

more robust APDs



- Hamamatsu 5*5 and 10*10 mm
- Perkin Elmer APDs

MCPs (Mickey Chiu)

Plasma Panel Sensors (SNW)

The Plasma Panel Radiation Detector Development Project

...beating TVs into particle physics instrumentation since 2015

Interest Group: Milind,Kirk, Thomas, Vitaly, Mickey, Grigor, Dino, Acker, (Abhay)

Free π^0 s for LBNE calibration

S.White, BNL-LBNE internal note

A large sample of exclusively produced π^0s with ~few GeV energy could be useful for calibration of energy scale and reconstruction efficiency. A naturally ocurring source would be π^0s produced by cosmic ray muons through Primakoff effect in water or Liquid Argon.

This exclusive process has been studied in low energy electroproduction on protons at Frascati (Belletini et al.), on Nuclei (HERMES) and even in proton-nucleus collisions (Ferbel).

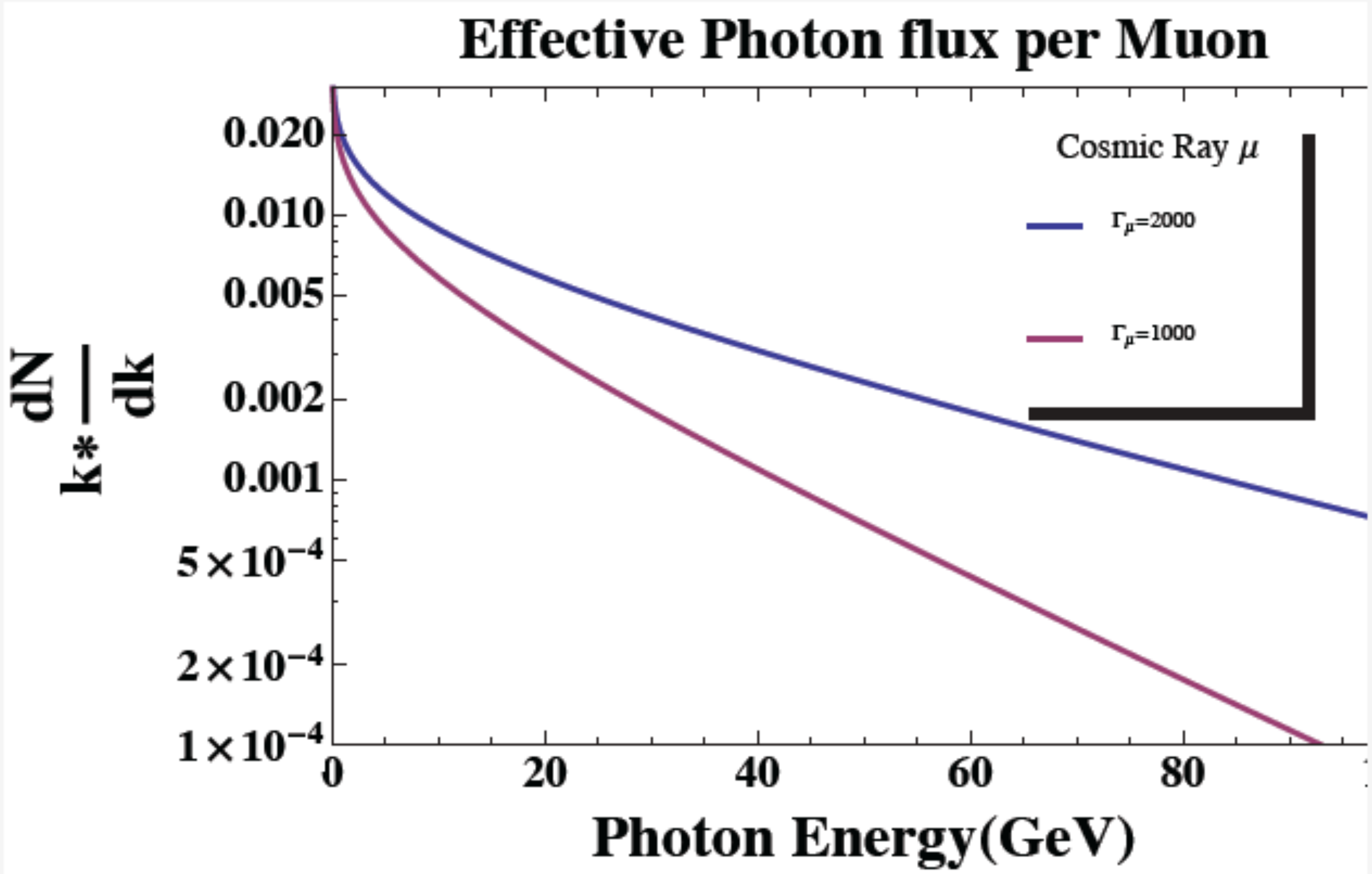
However it is much better understood in photoproduction and simulations recently done for JLAB measurements, which coincide with the characteristic photon energy from a ~100 GeV muon. Therefore we use here an analysis based on the Weizsacker-Williams(W-W) method. In this method the photon spectrum accompanying the cosmic ray muon is convoluted with the (weakly) energy dependent photoproduction cross section.

An analysis of the dominant processes of exclusive π^0 production (T. Rodrigues et al.) shows that nuclear coherent production (ie peripheral production by vector meson exchange) is somewhat larger than Primakoff on Argon and may be easier to measure. This process does not have a strong energy dependence. Also the mean photon energy from the W-W spectrum doesn't depend strongly on the muon energy so it may be possible to reliably predict the yield per track even with poor knowledge of the muon spectrum.

To calculate the W-W spectrum we use a form commonly used in the Heavy Ion Ultraperipheral community (A. Baltz et al.) which differs little from Fermi's original development of the Equivalent Photon Approximation . The usual integration over impact parameter from the muon track is cut off at $b = R_{Ar}$ since we are calculating an exclusive process.

```
<< Units`
<< PhysicalConstants`
Needs["PlotLegends`"]
Z = 1; A = ElementData["Argon", "AtomicWeight"];
rA = 1.2 * A^(1/3);
αEM = FineStructureConstant;
hbarc = PlanckConstantReduced * SpeedOfLight;
hbarc = Part[Convert[hbarc, Giga * ElectronVolt * Fermi], 1];
```

$$\mathrm{DNdk}[k\_,\Gamma\_] := \frac{2 Z^2 \alpha_{EM}}{\pi * k}\left(\frac{k * r_A}{\mathrm{hbarc} * \Gamma} * \mathrm{BesselK}\left[0, \frac{k * r_A}{\mathrm{hbarc} * \Gamma}\right] * \mathrm{BesselK}\left[1, \frac{k * r_A}{\mathrm{hbarc} * \Gamma}\right] - \frac{\left(\frac{k * r_A}{\mathrm{hbarc} * \Gamma}\right)^2}{2}\left(\mathrm{BesselK}\left[1, \frac{k * r_A}{\mathrm{hbarc} * \Gamma}\right]^2 - \mathrm{BesselK}\left[0, \frac{k * r_A}{\mathrm{hbarc} * \Gamma}\right]^2\right)\right)$$




```
Style[TableForm[
  {{a = Integrate[DNdk[k, 1000], {k, .5, 100}], b = Integrate[DNdk[k, 2000], {k, .5, 100}]},
   {Integrate[k * DNdk[k, 1000] / a, {k, .5, 100}],
    Integrate[k * DNdk[k, 2000] / b, {k, .5, 100}]}},
  TableHeadings → {{"Nγ>0.5 GeV", "<Eγ( GeV)>"}, {"Γμ=1000", "Γμ=2000"}}], 18]
```

	Γ_μ=1000	Γ_μ=2000
Nγ>0.5 GeV	0.0423594	0.0567329
<E_γ(GeV)>	4.55676	6.5115

```
σNC = 90(* nuclear coherent on Carbon in μb*);
dΩ = 2 * π * (Cos[.5 Degree] - Cos[2.5 Degree]);
σγ =
 dΩ * σNC * (ElementData["Argon", "AtomicWeight"] / ElementData["Carbon", "AtomicWeight"])^2
σμ = b * σγ
ρLAr = 2 * 10^22;
Nkmweekhz = 10^5 * ρLAr * σμ * 10^-30 (.6 * 10^6)
```

```
5.71584
```

```
0.324276
```

```
389.132
```

The 0.3μb exclusive π^0 production cross section is a significant fraction of the total muon nuclear interaction cross section.

There are roughly 0.1% exclusive π^0's per km of track length. Milind estimates that there would be a cosmic muon path length in the detector at the 300 ft. level of 30 km*Hz. In that case there are 30*389=12k exclusive π^0 s produced in a week. The rate in the water Cerenkov detector would be somewhat lower. These have very distinctive properties since they are produced at an angle of

$\theta_{peak} \sim 2 / (k * R\_Ar) \sim 2 / (E\_\pi^0 * R\_Ar)$

and would point back to the muon track.

These should be easier to detect than Primakoff produced π^0 s which are closer to the beam direction and have smaller production cross section. Incoherently produced π^0 s have a broader angular distribution and wouldn't be a significant background at this angle. But it's clear from the second figure that an additional parameter, $q_{/\!/}$, is available in photoproduction that isn't in electroproduction. On the other hand, it isn't clear that incoherently produced π^0 s (off individual nucleons) are any less useful. In incoherent events there would be a recoil nucleon roughly balancing the p_T of the π^0 and a few evaporation neutrons and γ's with ~6 MeV kinetic energy.

In that case the useful rate, which can be estimated from the 3rd figure, would be doubled.

```
σINC = 2 π * (Cos[1.5 Degree] - Cos[4.5 Degree]) * 90 *
  ElementData["Argon", "AtomicWeight"] / ElementData["Carbon", "AtomicWeight"]
```

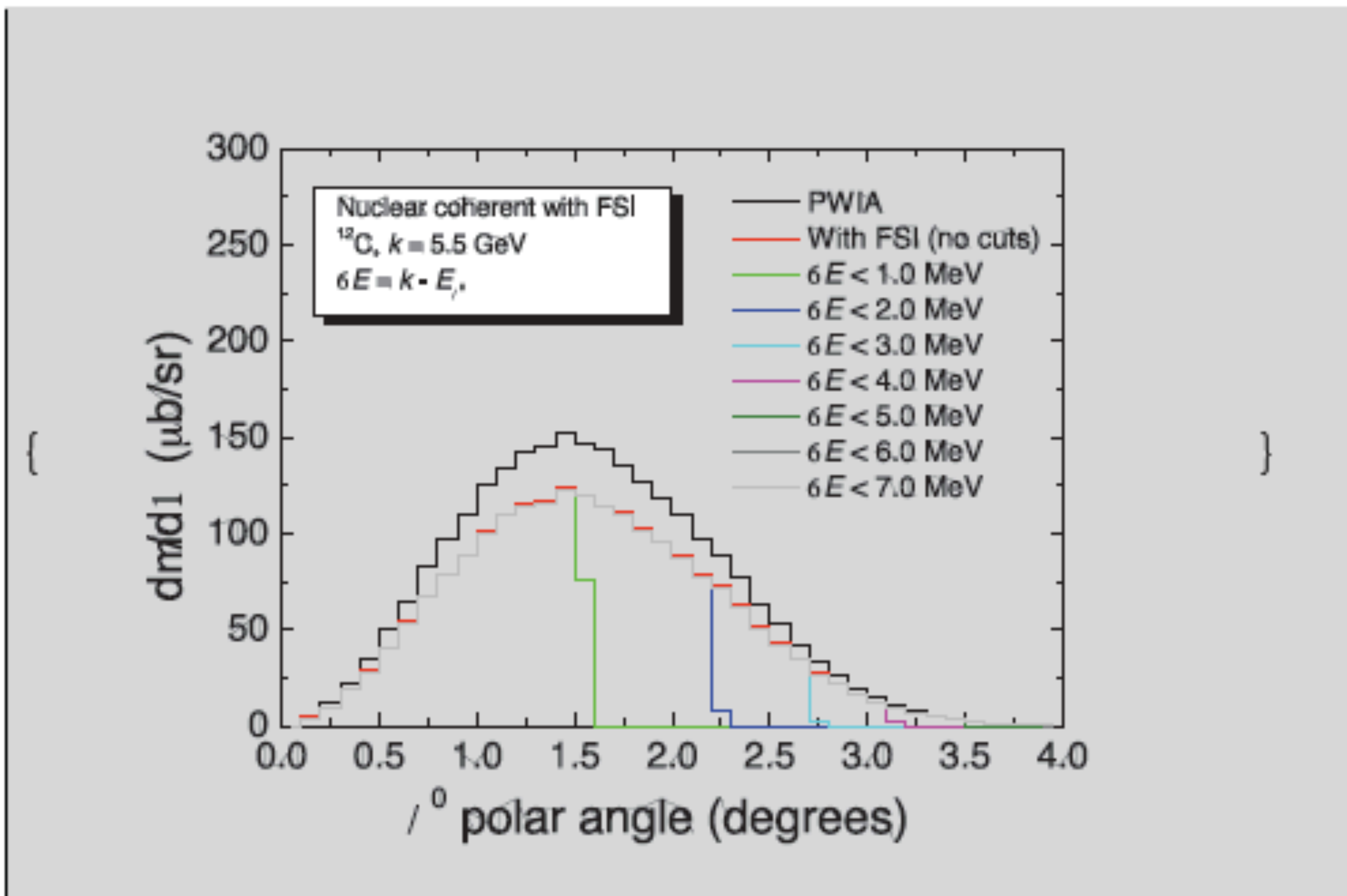
```
5.15345
```

Bibliography:

T. Rodrigues et al. "The nuclear matter effects in π0 photoproduction at high energies", Braz. J. Phys. vol.36 no.4b São Paulo Dec. 2006.
T. Ferbel, Acta Physica Polonica, B12 (1981) 12.
G. Belletini et al., Il Nuovo Cimento A Volume 40, Number 4 / December, 1965
A.Baltz et al. "The Physics of UltraPeripheral Collisions at the LHC" Phys. Rep. 458 N. 1-3 (2008)
E.Fermi, "On the Theory of Collisions between Atoms and Electrically Charged Particles"
http://arxiv.org/abs/hep-th/0205086v1

Appendix: Photoproduction Cross Sections

The following plots are from Rodrigues et al.



Conclusions

* Rutherford scattering idea for beam seems to work. We could develop a practical design for LBNE (LDRD)
* Huge rate of exclusive pi0's in LAr
* infancy of LBNE modelling should not prevent calibration R&D
* both modelling and R&D should be emphasized